EXPERIMENTS IN NUMERICAL FORECASTING OF TROPICAL STORM MOVEMENT

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OF TROPICAL STORM MOVEMENT

by

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ABSTRACT

Numerical prediction is rapidly becoming the most accurate approach to forecasting tropical cyclones. The numerical model in this study utilizes the U. S. Navy Fleet Numerical Weather Facility's (FNWF) so-called decomposition (SR) fields to produce geostrophic steering currents for tropical storms and/or hurricanes and typhoons.

Fifteen of the 1965 hurricanes and typhoons were used to obtain over 200 twelve and twenty-four hour storm predictions, in one-hour time steps, for each of the following FNWF analyses: 1000, 500, 200, 1000/500, 1000/200, and 500/200 -mb SR fields.

Results indicate that the 500-mb SR fields, including a statistical correction for latitude and/or longitude, yielded the least forecast error for Pacific typhoons with average 12 and 24-hour storm errors of 69 nm and 154 nm, respectively. Forecasts for Atlantic hurricanes verified best for 12-hour forecasts at 1000 mb, using a similar geographical modification, with an average error of 97 nm. For 24 hours the hurricanes were steered best at 500 mb, with modification, resulting in an average forecast error of 177 nm.

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TABLE OF SYMBOLS AND ABBREVIATIONS

H	height of constant pressure surface
g	gravity
Z	the pressure altitude in the standard atmosphere
f	the Coriolis parameter, $2\omega \sin\theta$
d,D	grid distance, 381 km at 60N
m	map scale factor
∇	del operator on a constant-pressure surface
∇^2	horizontal Laplacian operator on a constant-pressure surface
Vgi	component of geostrophic wind along the i axis of the FNWF grid
Vgj	component of geostrophic wind along the j axis of the FNWF grid
SR-( )	FNWF decomposition field at ( ) mb.
SR-( )/( )	FNWF decomposition field for layer between ( ) and ( ) mb
$\mathbf{V}$	vector geostrophic wind
$\hat{i}$, $\hat{j}$	unit vectors along cartesian coordinate axes, I, J, of the FNWF grid
x, y	scalar coordinates coincident with I, J axes.

1 Introduction

Accurate prediction of tropical storm[1] tracks is of vital interest to the military services and the general public. This interest has manifested itself by the many subjective and objective forecast techniques developed in the past ten years [1]. Prominent among them is the statistical model produced by the Travelers Research Center [2], the NHC64 model developed by the National Hurricane Research Laboratory [3] and the tropical steering program used by the United States Navy Fleet Numerical Weather Facility, (FNWF)[4]. The purpose of this study is to continue the search for an optimum forecast technique by utilizing numerically produced tropospheric "long wave patterns" to generate geostrophic steering currents for the tropical storms. Both typhoons and hurricanes from the 1965 storm season in the western North Pacific Ocean and the North Atlantic Ocean were used in this study. The numerical fields were supplied by FNWF.

All computations were made on the U. S. Naval Postgraduate School Control Data Corporation 1604 digital computer.

[1]The term "tropical storm" is used throughout to generally indicate both the storm and hurricane/typhoon stages.

2. FNWF Decomposition Fields.

The so-called decomposition fields used in this study, and currently used by FNWF in tropical storm forecasting, are isobaric height fields decomposed into additive components by applying a mathematical smoothing operator to the original height pattern for a prescribed number of times. [5],[4]. The smoothed height field, called the SR or residual analysis, simulates a long-wave circulation pattern which tends to be quasi-stationary. If the SR field is subtracted from the original height analysis, a small-scale (i.e., short wave) disturbance field (SD) is produced.

$$Z = SR + SD \qquad (1)$$

Tropical cyclones are examples of SD components. Figures 1 and 2 show examples of SR analyses at 1000 and 500 mb, respectively.

3. Synopsis of the Present Technique of Numerical Storm Prognosis at FNWF.

FNWF makes predictions of tropical storm movements upon request from the major Fleet Weather Centrals [4]. The Weather Centrals provide FNWF with the storm position and FNWF, in turn, produces a numerical forecast of the storm movement. The Weather Centrals use the numerical product as an aid in formulating the official forecasts which are distributed to the Fleet users [6], [7].

The numerical program which generates the steering trajectories is called HAT. The FNWF programs, including HAT, use a linear I, J grid, instead of latitude and longitude, to locate a point on earth [4]. The grid is a 63 x 63 square and is centered on the North Pole. There are 3969 intersections in the grid with a spacing of 381 km at 60 N. An arbitrary nine-point subset of the FNWF operational grid is shown in figure 3.

HAT presently uses a space mean geostrophic wind as the basic steering parameter. The influence of the storm is removed from the observed flow by a particular smoothing operation [4], the result being the large scale geostrophic flow. The storm is assumed to be a point vortex and to have no interaction with the large scale steering current.

The mean geostrophic steering wind has the form

$$\mathbb{V}_g = -g/f\left(\frac{\partial z}{\partial y}\hat{i} - \frac{\partial z}{\partial x}\hat{j}\right) = \mathbb{V}_{gi} + \mathbb{V}_{gj} \qquad (2)$$

and is determined at two levels, 1000 mb and 500 mb, at one-hour intervals up to 72 hours. At the 500mb level HAT uses hourly prognostic fields, smoothed in the prescribed fashion [4], to establish the mean wind. The low-level steering uses the most recent 1000-mb SR analysis.

HAT utilizes long term climatology in addition to the current data. As a result, three individual storm trajectories are produced. The first uses 500-mb data, the second uses 1000-mb SR analysis, and the third is an empirical combination of the first two and climatology.

4. Selection of Cases and Data.

Data fields were obtained from FNWF for the period beginning 15 August 1965 and ending 1 November 1965. All five 1965 hurricanes and ten typhoons occurred during this period. The storms were steered with the SR-1000, SR-500, SR-200 and the three corresponding thickness fields, 1000/200, 1000/500 and 500/200 mb.

The U. S. Fleet Weather Central/Joint Typhoon Warning Center, Guam (FWC/JTWCG) and U. S. Fleet Weather Facility, Jacksonville, Florida (FWFJ), are principally involved with tropical storms and each publishes a post analysis in the form of annual storm reports [6 and 7]. These reports contain tabulations of tropical storm positions for one calendar year. One of the many entries is the Best Track position. The Best Track positions are determined during post-season research and can be generally defined as a smooth line running through the fixes. The fixes are determined by aircraft reports, radar, and weather satellite pictures. The displacement of the Best Track from the fixes varies with the method of determining the fixes. In most cases the displacement lies within 10 to 20 nm [6].

5. Procedure.

This author wrote a numerical tropical storm steering program using FNWF's HAT program as the basic model. The principal changes made to the existent basic program allowed rapid cycling of many different storms on one computer run and the elimination of all empirical operations. In addition, only one SR field was used on a given computer operation.

The Best Track positions of the tropical storms were accepted as the initial and verifying positions.[2] The procedure used an SR analysis field to obtain the storm's steering current for a twelve-hour period. As an example, for the 00Z upper air observation, the 18Z Best Track position of the previous day was chosen as the initial storm position. The storm was then moved forward using 12 one-hour time steps. The error was determined by verification at the time of the 06Z Best Track position. The procedure was initialized with either the 00Z or the 12Z analysis and was iterated for all verifiable positions. The starting time and the number of iterations were dependent entirely upon the individual storm. The model was later modified for 24-hour prediction by increasing the number of one-hour time steps to 24, but otherwise proceded as outlined above.

Geostrophic steering components were determined using the finite difference form of the wind equation

$$\mathbb{V} = -\frac{gm}{2fD}\left[(Z_i^{j+1} - Z_i^{j-1})\hat{i} - (Z_{i+1}^{j} - Z_{i-1}^{j})\hat{j}\right] = \mathbb{V}_{g}i + \mathbb{V}_{g}j \qquad (3)$$

The sine function in the coriolis parameter, f, was modified at low

[2]Best Track positions in the Atlantic included some cases of tropical cyclones in the depression or extratropical stage.

latitudes to approach that at 7.2 degrees in order to avoid division by a number approaching zero. See figure 4.

Upon reading the initial position of the storm, the computer program translated latitude and longitude into an I,J position in the grid. From the one I,J position four surrounding positions were determined. These four points were as depicted in figure 3; I+1,J; I-1,J; I,J+1; and I,J-1.

An interpolation was made in the component geostrophic wind fields ($\mathbb{V}gi$, $\mathbb{V}gj$) to determine their respective values at each of the four grid points. The one-hour movement for each of the four points was simply the vector combination for the $\mathbb{V}gi$ and $\mathbb{V}gj$ components in knots. Each of the four points was then moved forward one hour and the centrum of the new positions was defined as the new "zero plus one hour" I,J position of the storm. The I,J values were reconverted back to latitude and longitude after the 12- or 24-hour prognostications.

Correlation and regression coefficients between true positions and prognostic positions were obtained in order to correct bias in the forecasts. Using the statistical corrections thus obtained, the storm predictions were then re-run for selected fields.

6. Results for Twelve-Hour Forecasts.

Table 1 lists the 12-hour forecast errors for each storm and the overall averages. The method giving the least error for a given storm is noted in the table by the asterisked values. The error for the SR-200 is highest with an overall average of 186 nm for a 12-hour movement. In addition, the thickness fields, using the SR-200, were also poor, with a 143 nm error for the SR 200/1000 and a 169 nm error for the SR 200/500.

The SR-1000 and the SR 500-1000 were nearly equal with overall error values of 108 nm and 105 nm, respectively. The SR-500 was overall the best with an average error of 89 nm. While the SR-500 did not always produce the least error it was, nevertheless, uniformly good for all storms.

After the hurricane and typhoon data were separated, it was interesting to note that the SR-1000 was best for hurricanes (Elena was an exception), with an average error of 101 nm. Comparing the performance of SR 500 and 1000 mb, SR-500 was best for typhoons (Lucy an exception), with an average error of 77 nm.

A plot was made of all storms but only two are included in this test. (See figures 5,6,7 and 8). It was noted that the predicted positions, especially north of 25-30 degrees, fell to the south of the verifying position in nearly every case. The shortcoming of underforecasting poleward storm movements is consistent with other numerical techniques [1]. However, an empirical correction was readily derived to improve forecast accuracy, as follows. Regression equations relating predicted latitude to true latitude and predicted longitude to

true longitude were derived using both the SR-1000 and SR-500 data. Inasmuch as there were 91 hurricane and 115 typhoon forecasts, the storms were stratified by ocean as well as grouped together. The pertinent regression equations are listed in table 3.

No single empirical correction was found to uniformly reduce all hurricane or typhoon prognostication errors. With reference to the SR 100-mb forecast verification (see table 1), a latitude correction applied to typhoons responded best with an overall average error reduction from 111 nm to 99 nm, while the longitude modification reduced the average error by only 2 nm to 109 nm. For the hurricanes, the latitude correction lowered the error by 1 nm to 100 nm while the longitude equation decreased the error to 97 nm. A combined latitude and longitude correction to hurricanes still produced an error of 97 nm.

The SR-500 forecasts were modified by a linear regression correction only when the prognostic position was north and east of the initial position. Twenty-five twelve-hour typhoon forecasts were affected by this change. The average forecast error for all typhoons was thereby reduced from 77 nm to 69 nm. Typhoons Mary and Rose moved north and west only and were not changed. The modification, in the case of typhoons Della and Lucy netted an increase in average error of 23 nm and 7 nm, respectively. The regression technique, using the SR 500 mb data, raised the average error for hurricane forecasts from 101 to 121 nm.

The SR steering method shows improvement over the official forecasts in three out of five hurricanes as may be seen in the last column of Table 1. The average official forecast and modified SR 1000 errors

are comparable, 94 and 97 nm, respectively. Twelve-hour official forecast errors for typhoons were not available for comparison.

The major reason that the numerical steering model, using the SR-1000 data did not produce a lower average, especially in the Atlantic, was the model's failure to predict the high latitude movements of hurricane Elena. Elena became a hurricane at about 23° north and continued as a hurricane to about 45° north. Typhoon Carmen and hurricane Carol also share similar problems when poleward of 25-30° latitude.

The reader will note the similarity in track orientation, if not position, in figures 5,6,7, and 8. When Carol made a loop in mid-Atlantic both the SR 1000 and the SR 500 made similar loops (figures 5, 6) even though displaced to the southeast. Moreover, both the SR 1000 and the SR 500 predicted the completion of the looping evolution. Such behavior is not unusual in the cases studied.

7. Results for Twenty-Four Hour Forecasts.

Table 2 lists the storms and composite 24-hour forecast errors for both official forecasts and the SR approach. Only the SR 500 was given extensive study for the 24-hour forecast because of the limited amount of time available. The SR 500 was chosen because of its good performance on the 12-hour predictions and because it out performed the SR 1000 and the SR 200 on the two 24-hour test cases, Carol and Carmen.

The SR 500 predictions, unmodified by latitude and/or longitude corrections, were slightly higher than the official forecasts for both hurricanes and typhoons.

The 24-hour forecasts for SR 500 were modified for both typhoons and hurricanes as a single group in a manner similar to the 12-hour SR 500 predictions. However the modification statistic was derived only for those storms forecasted to move towards the northeast.

All hurricane prediction errors decreased with the modification except for Anna. The average was reduced from 198 nm to 177 nm. The average storm error, using official forecasts, was 187 nm for hurricanes [7].

The prediction error for typhoons by storm was reduced from 168 nm to 154 nm with the modification. Two typhoons, Lucy and Olive, showed increased average forecast errors of 20 nm and 12 nm, respectively, when modified. Again, as in the 12-hour predictions, typhoons Mary and Rose did not move toward the quadrant east of north and, therefore, were not modified. The average official forecast error for typhoons was 153 nm [6].

The storm tracks (figures 4 and 6) for the 24-hour SR 500 follows

the Best Track quite well. When Carol began her mid-Atlantic loop, the 24-hour prediction shows a similar but nondescript trajectory. The completion of the looping action for Carol on 25 September 1965 was forecasted very well with both the actual and forecast positions indicating definite termination of the recurvature path.

The 24-hour forecasts also under predicted northward movement for storm positions poleward of 25° north, similar to the 12-hour forecasts. The magnitude of the error was greater than for the 12-hour predictions as can be seen in the regression equations. (See table 3.)

8. Errors Inherent in Computations.

Both the initial and the forecast positions of each storm were printed by the computer program. An unexpected result came after checking the initial position for accuracy. Of the 122 positions given detailed checks, 71 were correct, 46 were in error by 0.1 degree of latitude or longitude, and 5 were in error by a 0.1 degree on both latitude and longitude. No pattern or position bias was found for the errors.

Both the data cards and the basic computer program were found to be correct. The explanation for the loss of accuracy is in the conversion of latitude and longitude to I, J values and the reconversion from I, J back to latitude and longitude. An insufficient number of Binary Digits are allotted in the sub-routines used for the fractional portions of both I, J values and latitude and longitude in the conversion sequences. For example only four Binary Digits are used in the fractional portion of the conversion of I, J to latitude and longitude. A minimum of seven Binary Digits would be required to insure one decimal place accuracy.

9. Conclusions.

a. It is concluded that the 12- and 24-hour movement of tropical storms can be predicted using the FNWF decomposition analyses (SR fields) with accuracy competitive to that of operational techniques now in existence.

b. Secondly, it appears that typhoon movement can be predicted more accurately than hurricane movement.

c. Further, the observed 12-hour hurricane motion was found to correlate better with the SR-1000 while the 24-hour movements correlated better with the SR-500.

d. In addition, the SR-500, modified for latitude bias, improves the typhoon forecasts for both 12 and 24-hours.

Several facts temper the success noted above. One, the use of Best Track position here gives the official forecast a relative handicap, and two, the number and time of the experimental forecasts differ from the official forecast sample. Thirdly, it is to be noted that the SR field employed represents the analysis at the midpoint of the 12-hour forecast interval while the 24-hour forecast used the analysis one-quarter of the way from initial to verification time. Other more exacting tests may now be employed as the subject research suggests success in the realm of a feasibility study.

10. Recommendations.

1. The numerical geostrophic steering should be tried in a 700-mb SR field and the results compared to the SR-1000 and SR-500 results. The 700-mb level is used in several current prediction models. In addition, some other intermediate level between the 1000-mb and 500-mb levels may well be superior.

2. A vertically integrated wind over the entire atmosphere ought to be given extensive testing as a steering current.

3. The prognostic SR fields for 24 and 48 hours may be the media for improving tropical storm extended forecasts.

4. The number of binary digits should be increased in the fractional portions of the conversions and re-conversions of latitude and longitude to I, J, in order to improve accuracy in tropical storm forecasts.

5. Publication of 12-hour official forecast errors is most desirable, since this time period should be considered fully prior to attempting extended predictions.

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AVERAGE TWELVE-HOUR FORECAST ERROR

Tropical Cyclone	SR-1000	SR 500	SR 200	SR 1000/200	SR 500/200	SR 1000/500	Mean	Official
Hurricanes								
Anna	60*	82				98	80	119
Betsy	78*	83	168	142	172	96	123	67
Carol	93*	127	290	143	171	101	154	105
Debbie	58*	89	208	167	196	90	135	65
Elena	215	194*	306	217	254	196	230	114
Hurricane Average:	101*	115	286	167	198	116	144	94
Typhoons								
Lucy	53*	84				133	90	
Mary	44	28*				65	46	
Olive	72	61*	112	121	139	81	98	
Rose	140	34*	356	168	234	77	168	
Shirley	140	122*	146	132	134	129	134	
Trix	134	97	92*	81	111	100	103	
Virginia	146	104*	181	191	260	132	169	
Bess	123	84	137	130	132	75*	114	
Carmen	131	67*	95	89	93	86	94	
Della	130	85*	136	134	128	117	122	
Typhoon Average:	111	77*	144	131	154	100	114	
Overall Average:	108	89*	186	143	169	105	133	

*Least Forecast Error

Table 1

AVERAGE TWENTY-FOUR HOUR FORECAST ERROR

Tropical Cyclone	Official Forecasts	SR 500	Modified SR 500
Hurricanes:			
Anna	217	149	205
Betsy	130	157	146
Carol	192	181	151
Debbie	135	149	121
Elena	260	353	265
Hurricane Average:	187	198	177
Typhoons:			
Lucy	169	216	236
Mary	107	111	111
Olive	138	129	141
Rose	55	139	139
Shirley	231	230	182
Trix	138	187	135
Virginia	289	200	182
Bess	106	120	105
Carmen	148	156	124
Della	152	196	189
Typhoon Average:	153	168	154
Overall Average:	164	178	163

Table 2

REGRESSION EQUATIONS FOR SELECTED SR FIELDS

La(Lo) = unmodified latitude (longitude) prognostic positions, in deg.
La'(Lo') = modified latitude (longitude) prognostic positions, in deg.

1. Hurricanes: SR 1000, Latitude, 12-hour forecast,
   $La' = 0.24887 + 1.02211 \times La$

2. Hurricanes moving with component toward the north and east: SR 500, Latitude, 12 hour forecast,
   $La' = -0.83029 + 1.09578 \times La$

3. Hurricanes: SR 1000, Longitude, 12-hour forecast,
   $Lo' = -0.88912 + 1.00205\ Lo$

4. Typhoons: SR 1000, Latitude, 12-hour forecast,
   $La' = -\ 1.43561 + 1.10895 \times La$

5. Typhoons moving with component toward the north and east: SR 500, latitude, 12-hour forecast,
   $La' = -1.65408 + 1.11824 \times La$

6. Typhoons: SR 1000, Longitude, 12-hour forecast,
   $Lo' = -0.93399 + 1.00722 \times Lo$

7. Hurricanes and typhoons moving with component toward the north and east: SR 500, latitude, 24-hour forecas
   $La' = -\ 1.10658 + 1.114813 \times La$

Table 3

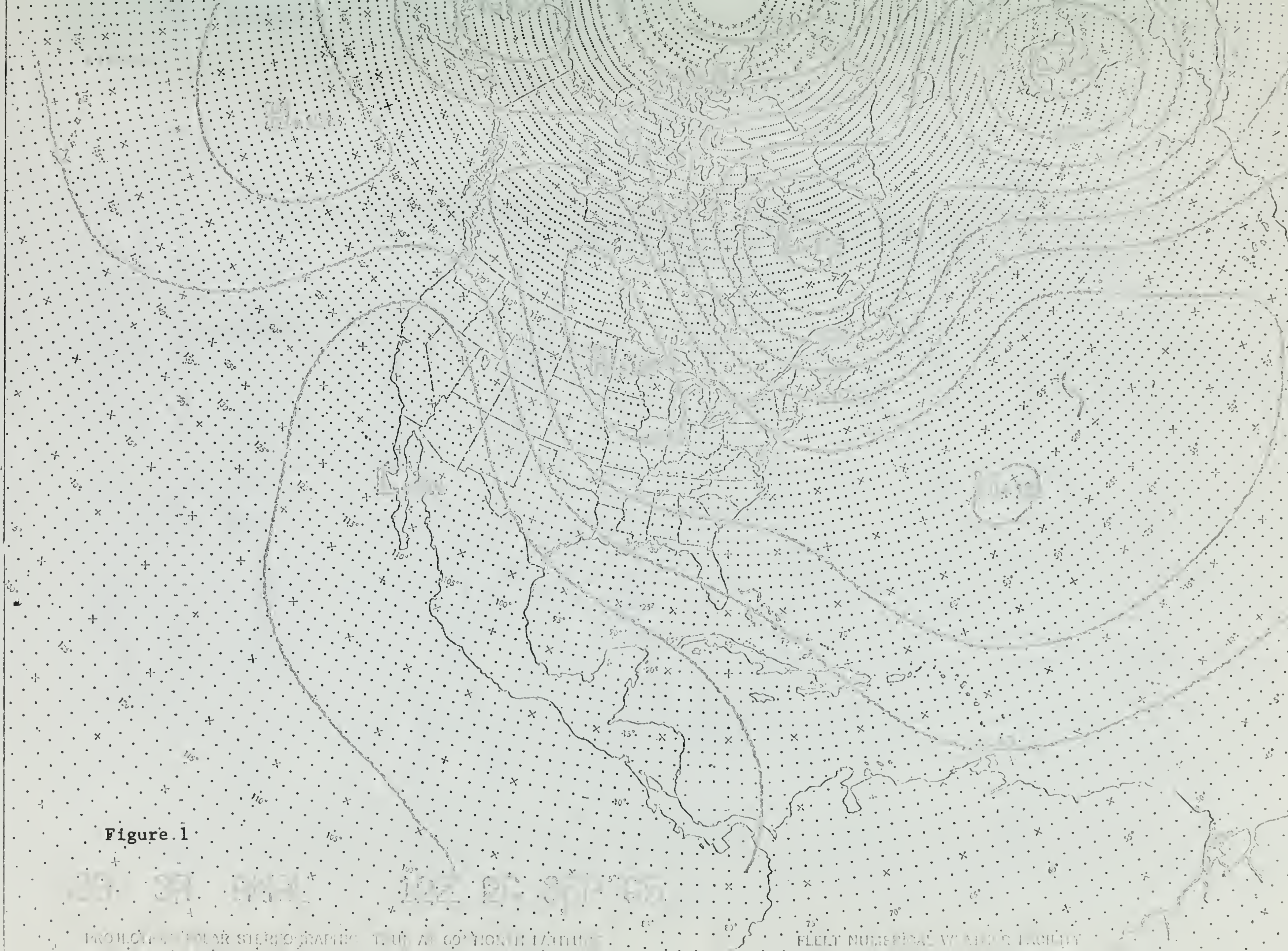

Figure 1

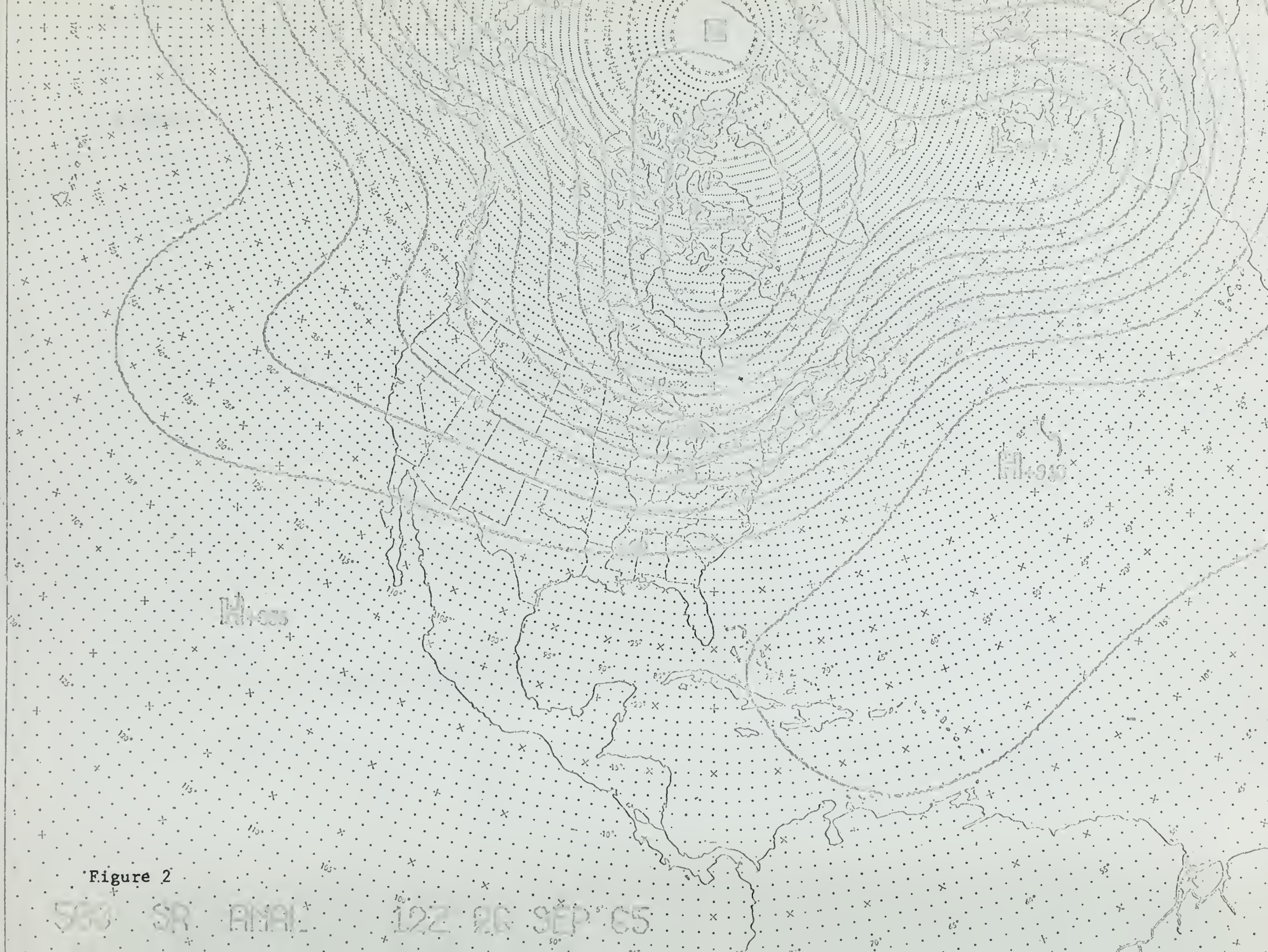

Figure 2

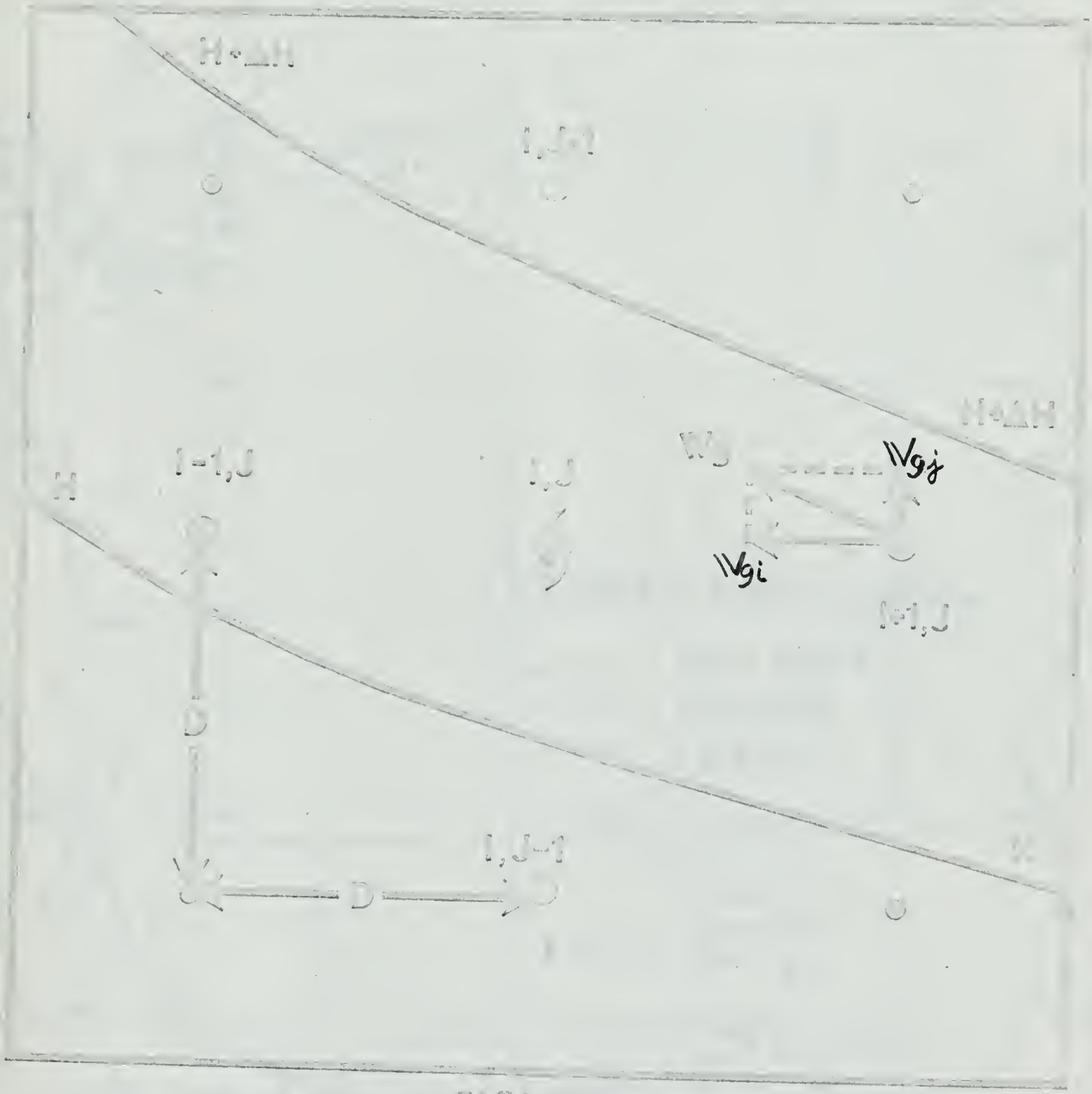

FIGURE 3

PREDICTION GRID WITH SUPERIMPOSED ISOLINES OF HEIGHT AND A GEOSTROPHIC WIND VECTOR

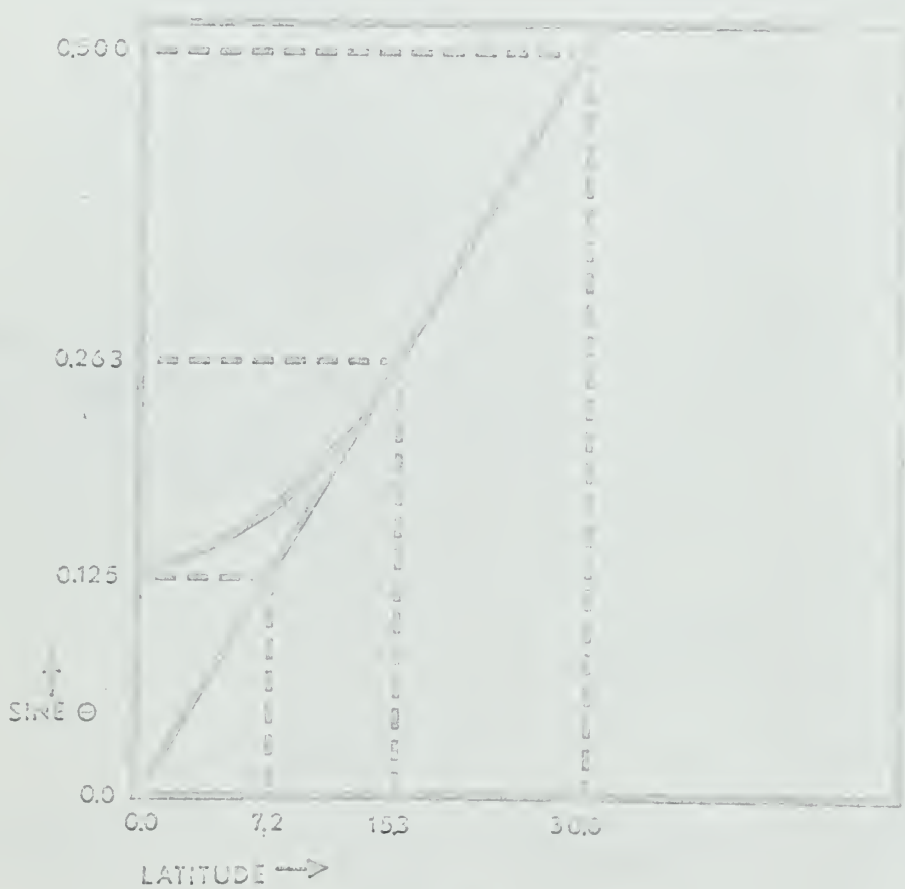

FIGURE 4

SINE MODIFIED AT LOW LATITUDE
TO APPROACH THE VALUE AT 7.2°

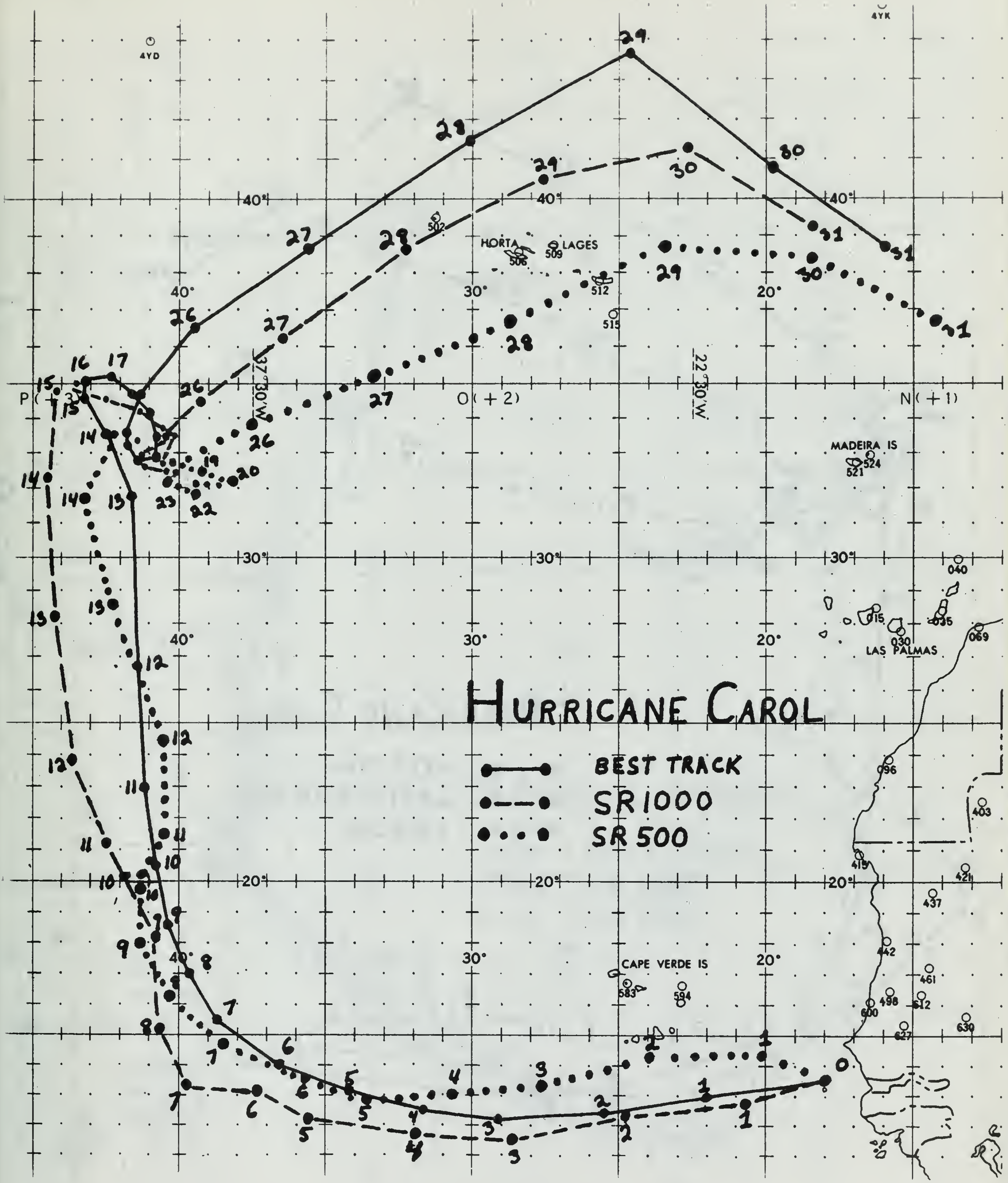
HURRICANE CAROL
BEST TRACK
SR1000
SR500
HORTA
LAGES
MADEIRA IS
LAS PALMAS
CAPE VERDE IS
22°30'W
37°30'W
P(+3)
O(+2)
N(+1)

Figure 5

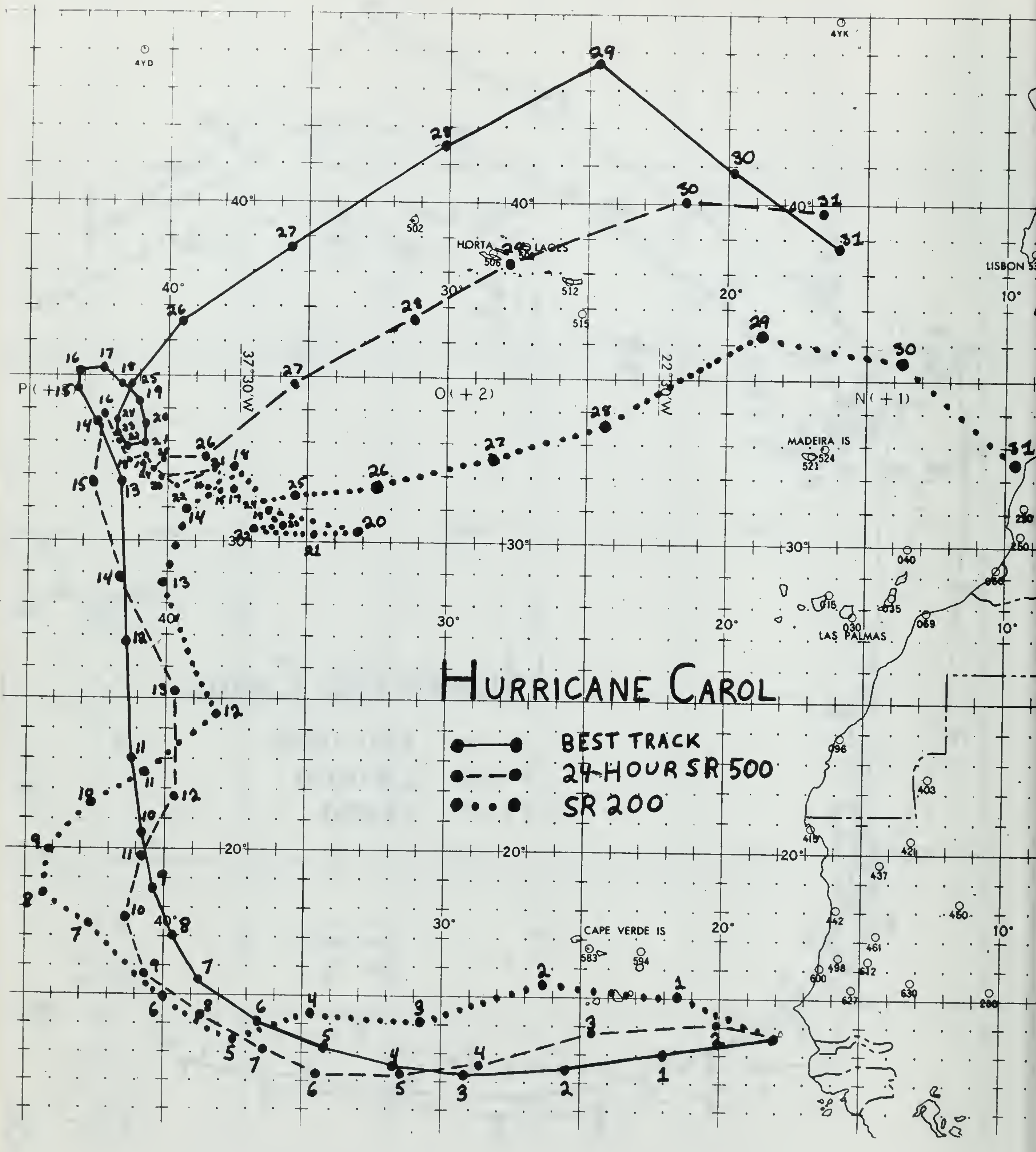
HURRICANE CAROL
BEST TRACK
24-HOUR SR 500
SR 200
HORTA
LAGES
MADEIRA IS
LAS PALMAS
CAPE VERDE IS
LISBON
37°30'W
22°30'W
P(+15)
O(+2)
N(+1)

Figure 6

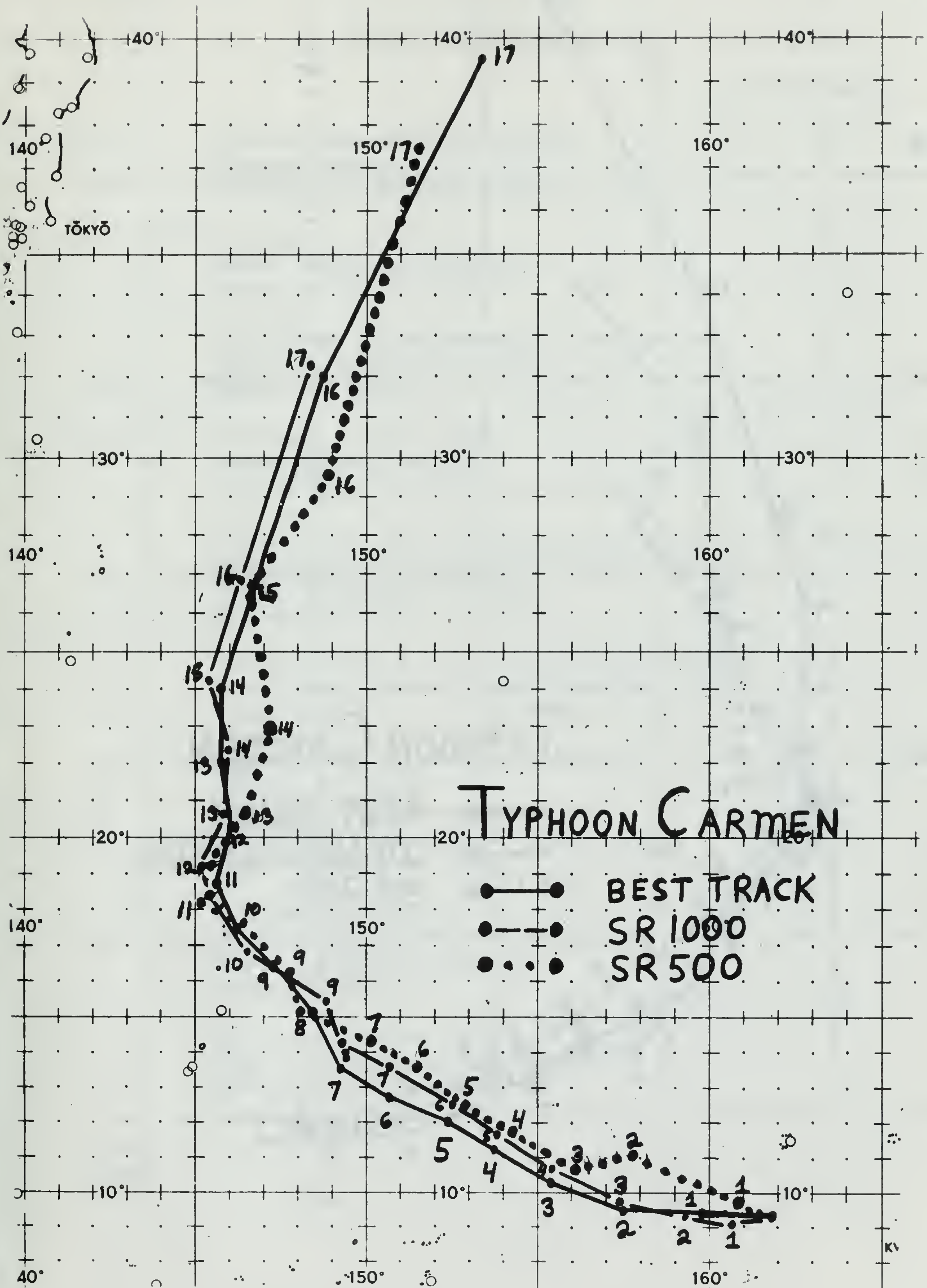
TYPHOON CARMEN
BEST TRACK
SR 1000
SR 500
TŌKYŌ
40°
30°
20°
10°
140°
150°
160°

Figure 7

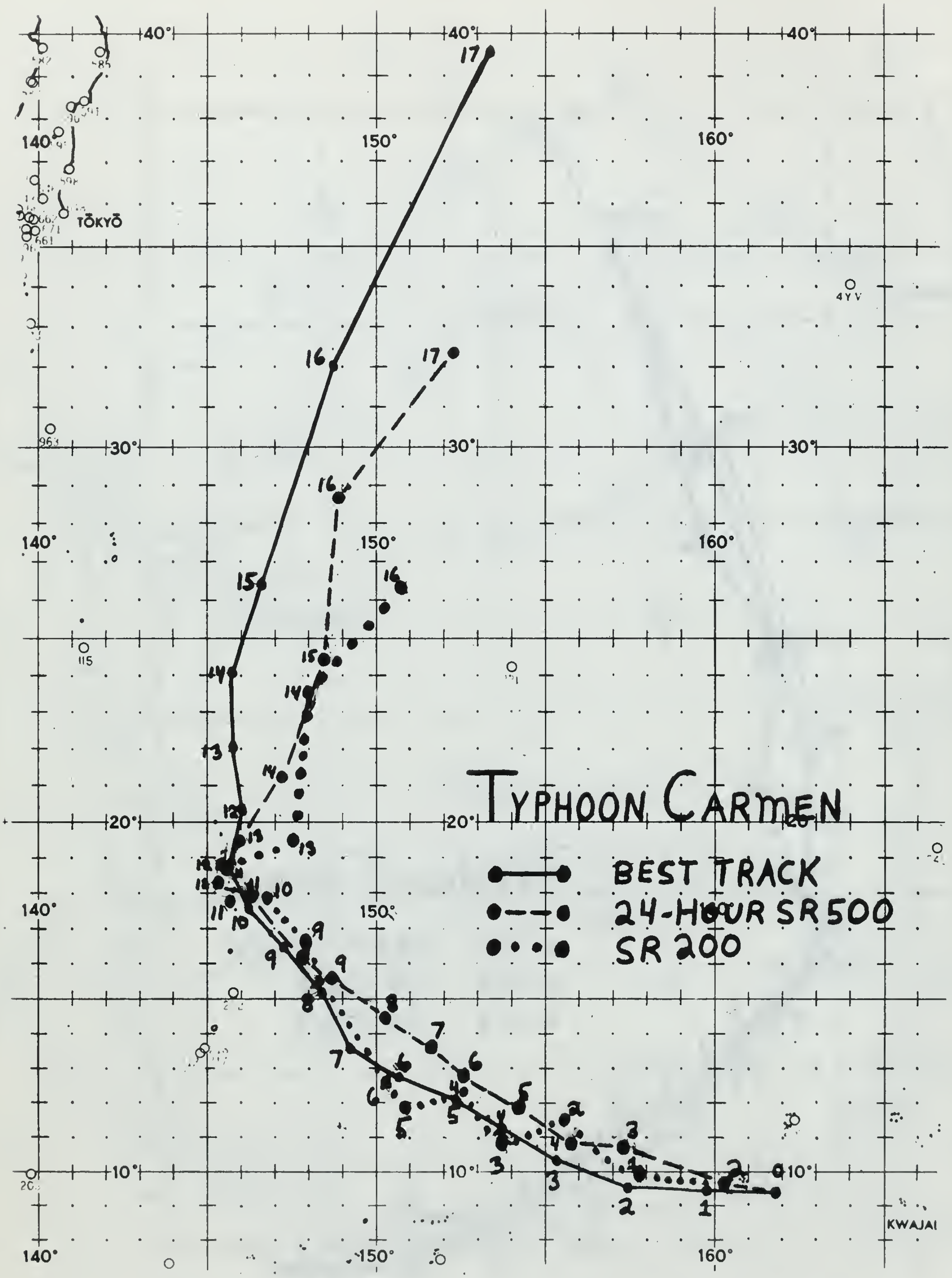
TYPHOON CARMEN
BEST TRACK
24-HOUR SR500
SR 200
TOKYO
KWAJAI
40°
30°
20°
10°
140°
150°
160°

Figure 8

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13. ABSTRACT

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